Characterization and Analyses of Valves, Feed Lines and Tanks Used in Propellant Delivery Systems at NASA SSC

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Denver, CO
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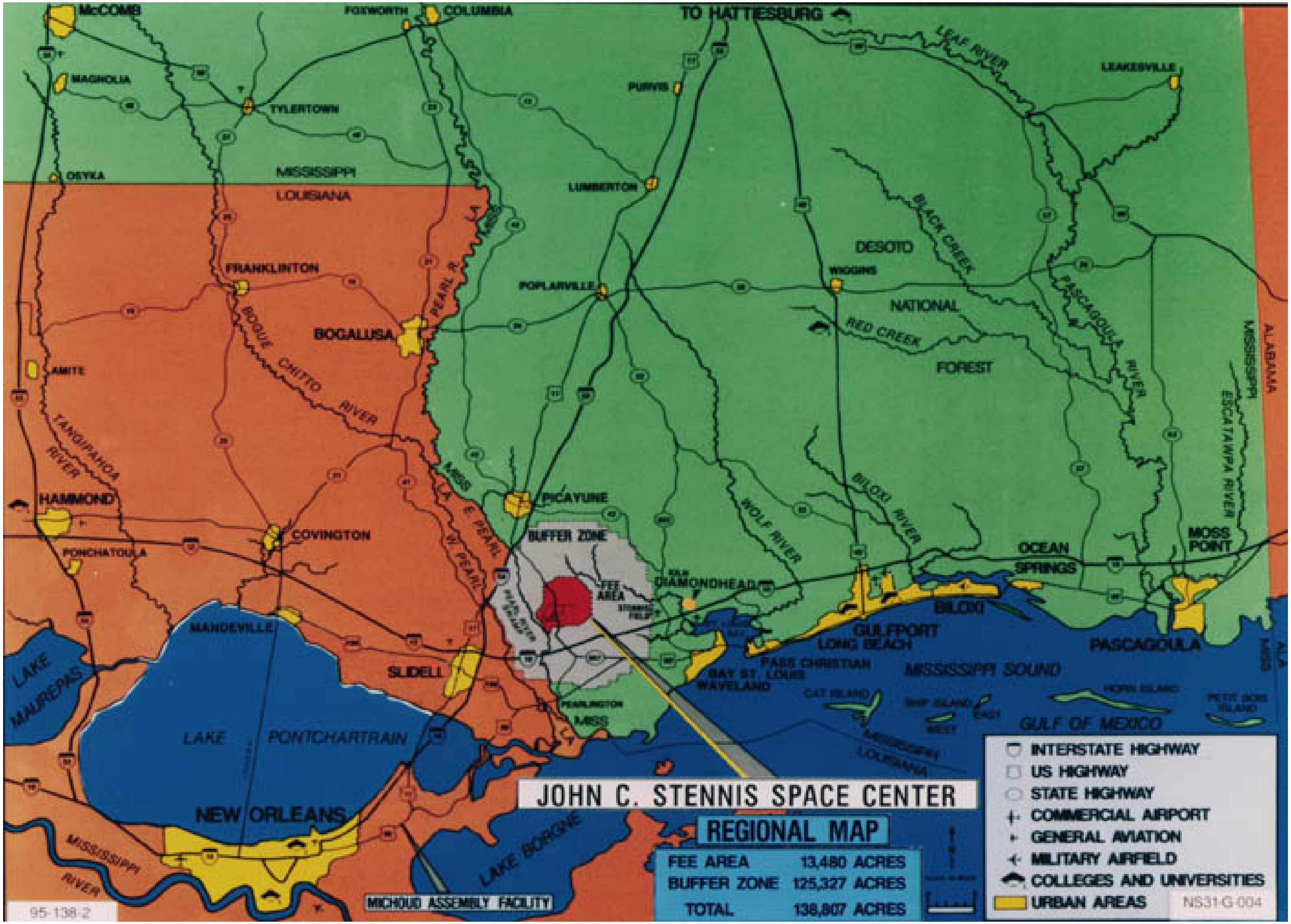
SSC Regional Map



Complete Suite of Test Capability and Expertise

E-1 Stand

High Press., Full Scale Engine Components

E-2

High Press.

Mid-Scale

& Subscale

E-3

High Press.

Small-Scale

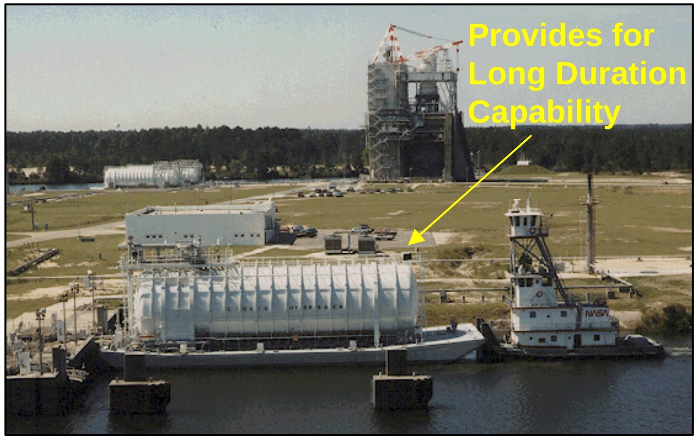
Subscale

A-1 … Full Scale Engine Devt. & Cert … A-2

B-1/B-2 … Full Scale Engine/Stage Devt. & Cert

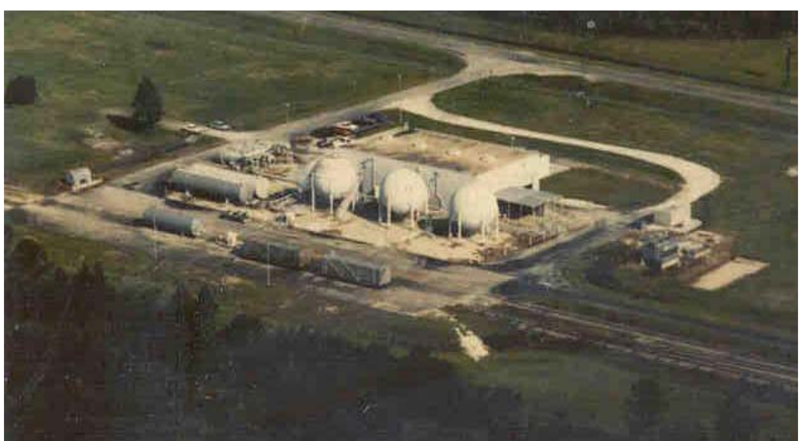
Components …Engines … Stages

SSC Support Facilities



Cryogenic Propellant Storage Facility
Six (6) 100,000 Gallon LOX Barges
Three (3) 240,000 Gallon LH Barges

High Pressure Industrial Water (HPIW)
330,000 gpm Delivery System



High Pressure Gas Facility (HPGF)
(GN, GHe, GH, Air: ~ 3000 to 4000 psi)

Additional Support

- Laboratories
  - ✓ Gas and Material Analysis
  - ✓ Measurement Standards and Calibration
  - ✓ Environmental
- Shops
- Utilities

NASA SSC Design & Analysis Division

Design and Analysis Division

- Configuration Management
- Records Retention DB Management

Mechanical and Component Systems

- Cryogenic Propellant Systems
- Storable Propellant Systems & HPIW
- Hydraulics/pneumatics Systems
- Press Gas/Purge Systems (TBA)
- Components
- Materials
- Ancillary Systems
  - TMS, Measurement Uncertainty
  - Standards & Specifications

Electrical Systems & Software

- Data Acquisition
- Instrumentation & Signal Conditioning
- Controls & Simulation
- DACS Lab Management
- Data Systems Management
- Ancillary Systems/Electrical Power

Systems Analysis & Modeling

- Modeling and Analysis development and integration into RPT
- Fluid Mechanics/Thermal Analysis of Propellant Systems
  - Liquid
  - Gas
- CFD
- Structures/Loads Analysis
- Thermal/Heat Transfer Analysis

Organization Goal:

- **Develop and maintain propulsion test systems and facilities engineering competencies**
  - Unique and focused technical knowledge across respective engineering disciplines applied to rocket propulsion testing. e.g.,
    - Materials selection and associated database management
    - Piping, electrical and data acquisition systems design for cryogenic, high flow, high pressure propellant supply regimes
    - Associated analytic modeling and systems analysis disciplines and techniques
    - Corresponding fluids structural, thermal and electrical engineering disciplines

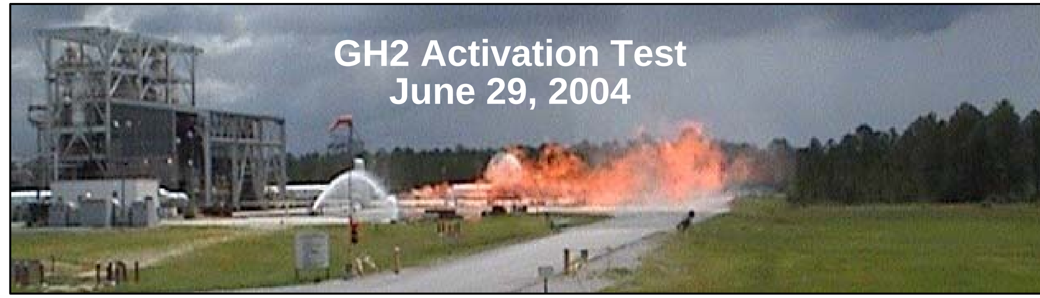
Integrated Facility Simulation and Analysis

- SSC Has Developed & Implemented Effective Analytic Modeling & Simulation Tools To Support Propulsion Testing
  - Rocket Propulsion Test Analysis (RPTA) Model (FORTRAN) Used to Simulate Propulsion Test Facility Systems (e.g., LOX Run System)
    - ✓ Heritage of Model Dates to Pressurization and Propellant Systems Design Tasks for Space Shuttle and X-33
    - ✓ Model Adapted, Validated and Currently Used at SSC to Simulate Facility Pressurization and Propellant Systems
  - Fluid Flow Analysis (Flowmaster)
  - Finite Element Analysis (ANSYS)
  - Computational Fluid Dynamics (CRUNCH CFD Code) Used for Select Propulsion Test Situations
- Have Experienced Analysis Team that Routinely Solves Pressurization and Propellant System Problems
- Integrated Facility Simulation and Analysis Has Led to Substantial Project Cost and Schedule Savings

Integrated Facility Simulation and Analysis

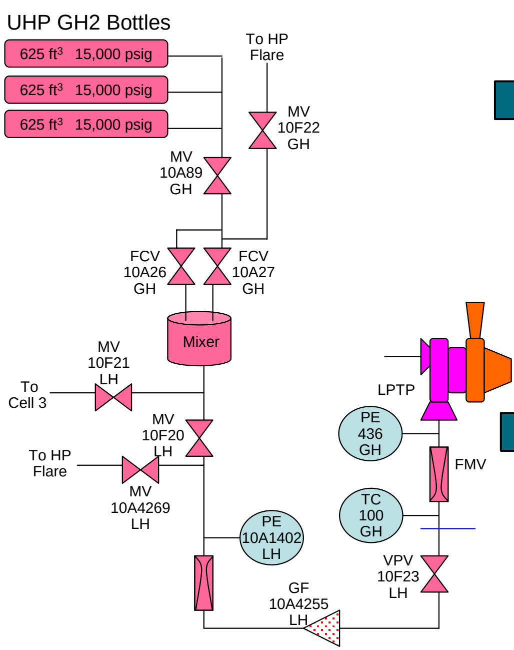
- Analytic Tools Available for Propulsion Test Facility Modeling & Analysis
- Comprehensive Propellant System Thermodynamic Modeling & Test Simulation

Integrated Performance Modeling Capabilities Substantially Improves Understanding & Knowledge of Test Systems Performance that has Translated to Efficient Test Facility Design, Activation & Test Operations

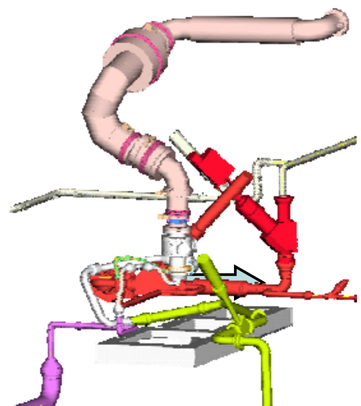


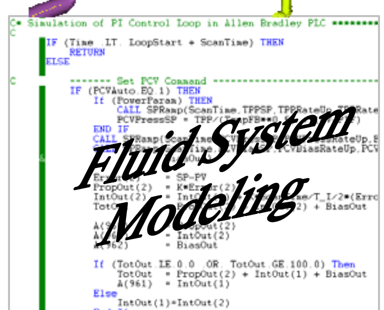
Test and Data Analysis

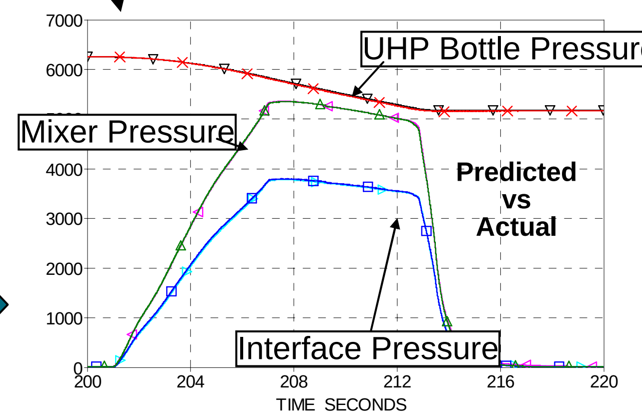
System Design

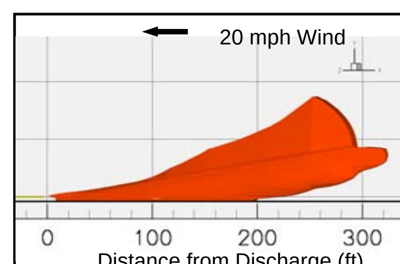


Modeling







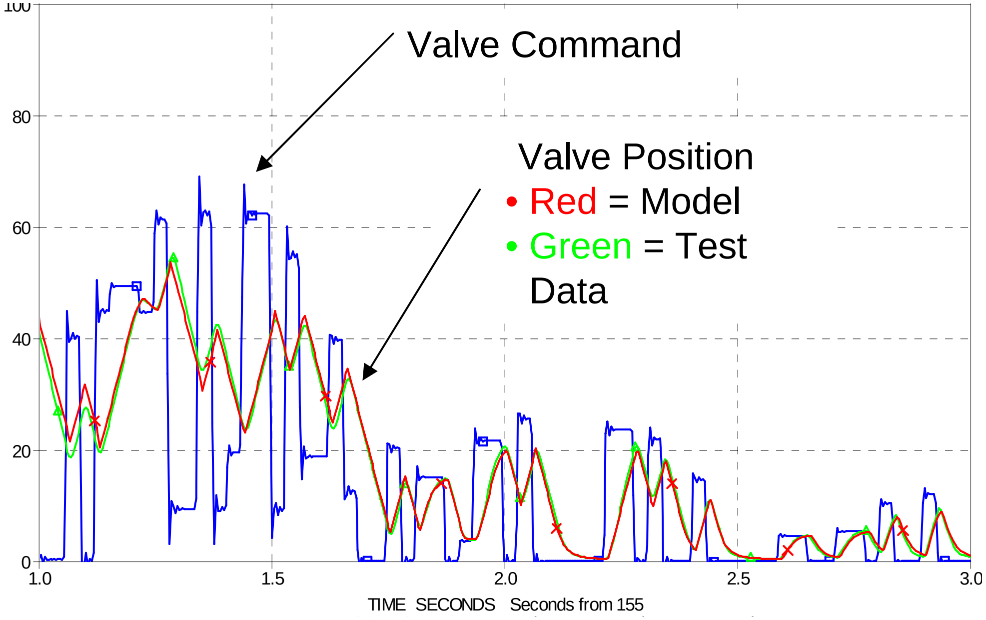


Advanced Capabilities in CFD Modeling & Analysis

Rocket Propulsion Test Analysis (RPTA) Model

- Temporal Transient Thermodynamic Modeling of Integrated Propellant Systems
- Thermodynamic Control Volume Solver Model Accurately Models High-Pressure Cryogenic Fluids and High-Pressure Gaseous Systems. Model Features Include:
  - High-Fidelity Pressure Control Valve (PCV) & Closed Loop Control System Model
- RPTA Model Validated Through Test Data Comparisons
  - IPD Fuel Turbopump, RS-84 Sub-Scale Pre-Burner, RS-83 Pre-Burner Cold Flows, SSME Flowliner Activation & IPD Engine System

Pressure Control Valve (PCV) Model Developed & Validated



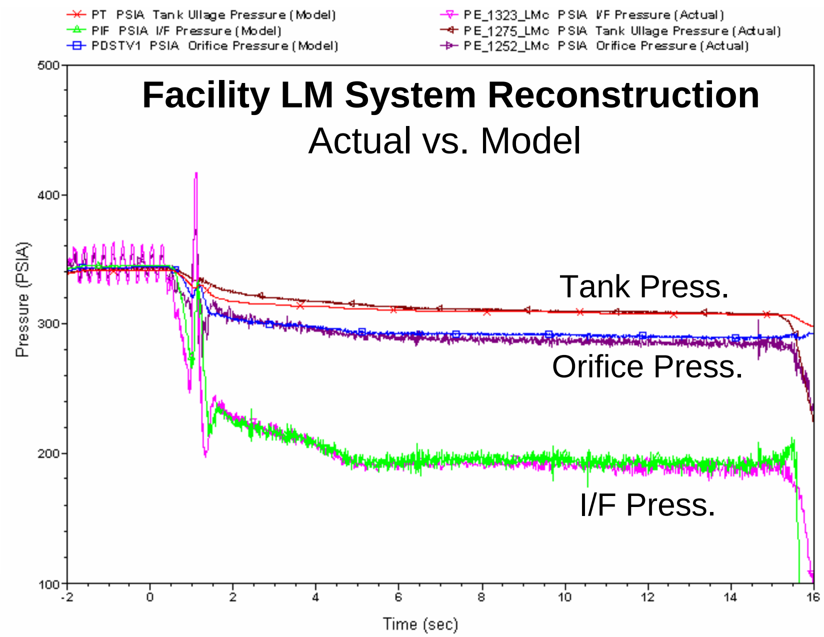
A Significant Feature of the RPTA Model is the Coupling of Control Logic (Electro-Mechanical Process) with Thermodynamic Processes

RPTA Model Application Example

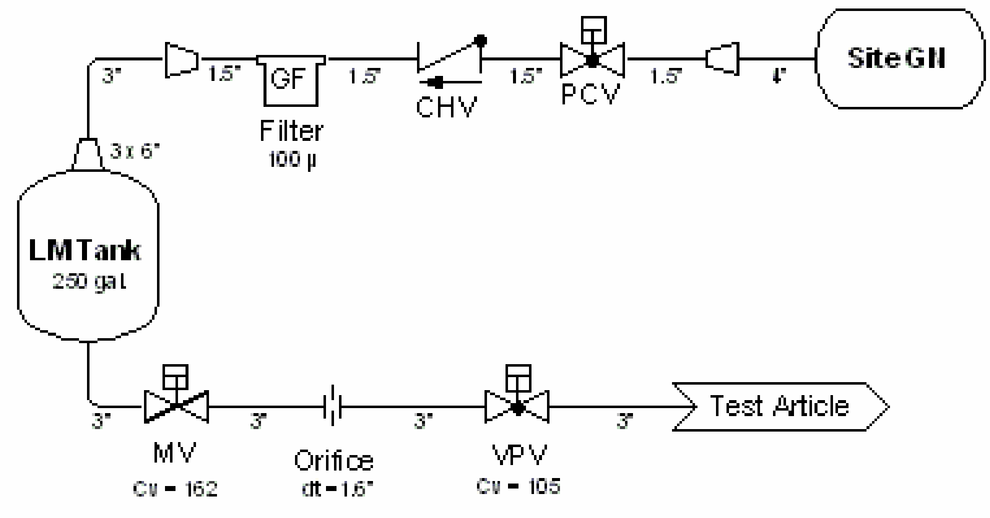
LOX/Methane Testing at E-3 (Nov. 2006)

Facility Activated and Test Performed

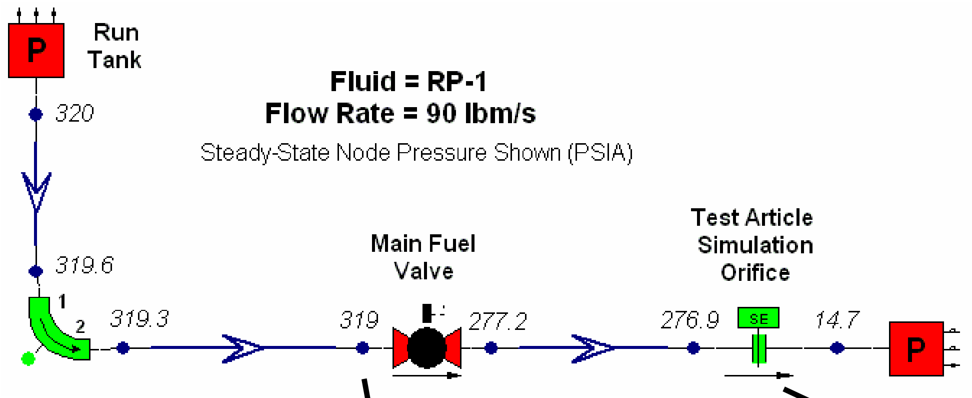
- **Liquid Methane (LM) & Liquid Oxygen (LOX) Propellants Used**
- **Facility Model Results and Facility Test Activation Results Agree Well**
- **Test Capability: ~25 seconds**



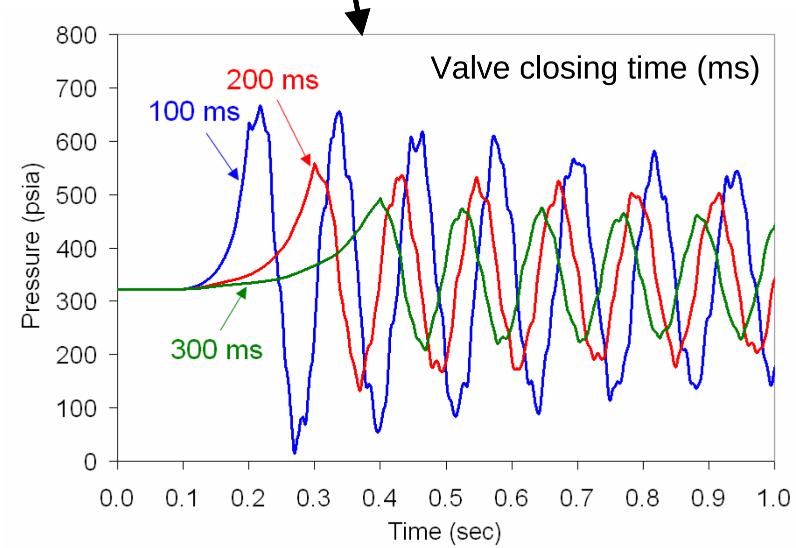
LM System Schematic



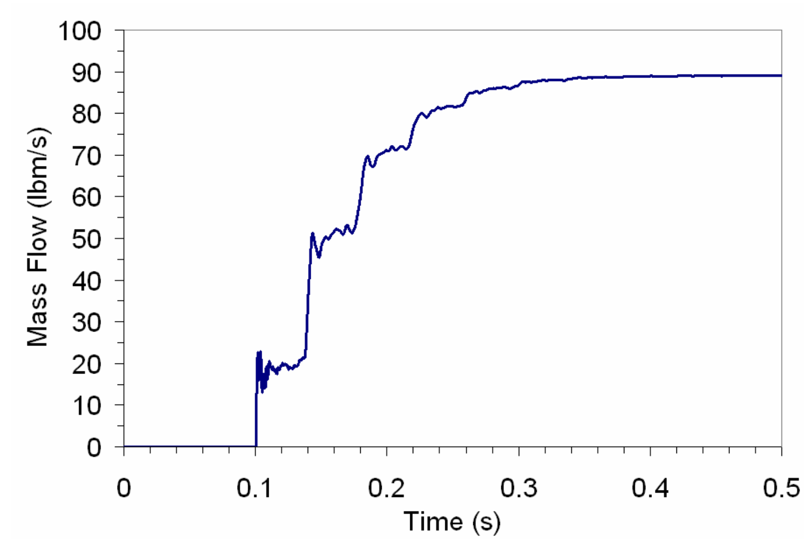
Comprehensive & Rapid Piping System Design & Analysis Capability



- Commercial Tools Employed to Augment Analysis
- Example: *FlowMaster* Piping System Analyzer
  - Allows for Steady-State or Transient Analysis, Compressible or Non-Compressible Flow
  - Includes Heat Transfer, Flow Balancing, Priming & Sizing Analysis



Water Hammer Effect Due to Rapid Closure of Main Fuel Valve



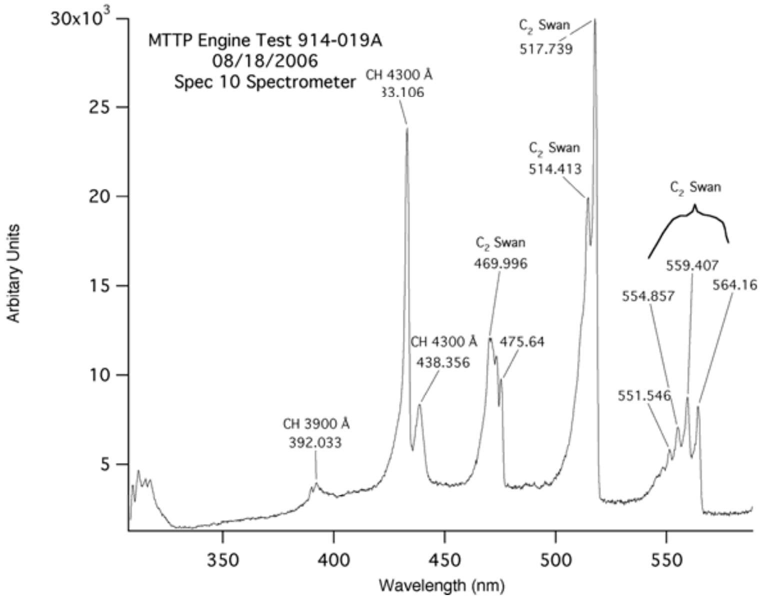
Propellant Flow to Test Article Due to Rapid Opening of Main Fuel Valve

Recent Project: Methane Technology Testbed Project (MTTP)

- MTTP Provides Portable, Small-Scale Propulsion Test Capabilities
  - Can Support Gaseous Methane, Gaseous Oxygen, Liquid Methane & Kerosene-Type Propellants
  - Capable of Supporting Engines up to 1000-lbf Thrust
- Tested 50-lbf Thruster (right)
  - Plume Diagnostics
  - Gained Methane Experience

Night Firing of MTTP Thruster

MTTP Test Skid



Exhaust Spectrum for GOX/GM Combustion

Recent Project: 14’’ Valve Test
Description of Test Objectives

Test Objectives

- Collect Data Needed to Support a Decision to Install a 14” Valve (26,000 lb) on the E-1 Test Stand as the High Pressure (8,500 psi service) LOX Tank Isolation Valve
- Determine the Behavior of the Valve in Simulated Operating Conditions
- Determine the 14’’ Valve Bonnet and Body Steady State Temperatures

Test Details

- Conducted Valve Chill Down Test at the E-2 Test Stand
- Used Liquid Nitrogen (LN) to Chill Down the Valve
- Instrumented Valve with Multiple Thermocouples on the Valve Body and Stem
- During Chill Down Operations, the Valve was Cycled Multiple Times to Test Proper Valve Operation at Low Temperatures

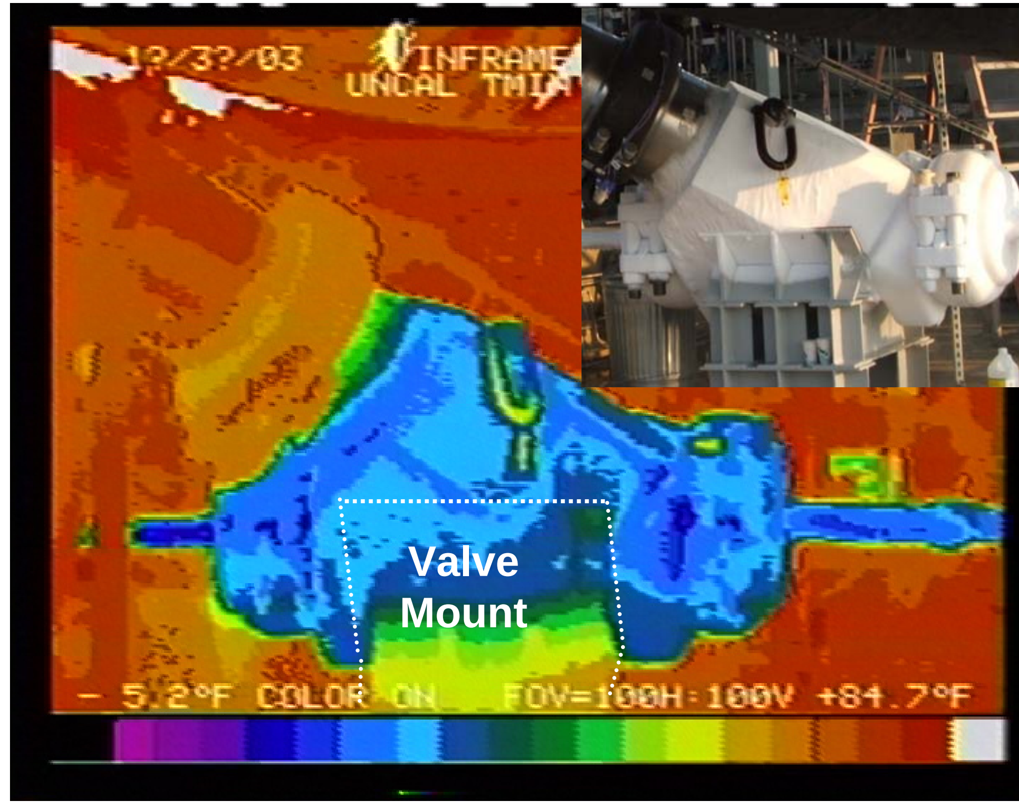
14’’ Valve During Chill Down

14’’ Valve Test Results

Test Results
- Test Lasted About 24 Hours
- About 6500 gal of LN Was Used for the Valve to Reach a Steady State Condition
- Boil Off Results Were Used to Calculate the Steady State Heat Load of the Valve

Analytical Accomplishments
- Identified Issue with Asymmetric Bonnet Wear at Cryogenic Temperatures
- Verified Analytical Predictions for the Heat Load of the Valve
  - Determined the Valve Heat Load
  - Determined the Valve Chill Down Time Constant
  - Test Results Will Be Used to Guide Bonnet Re-Design

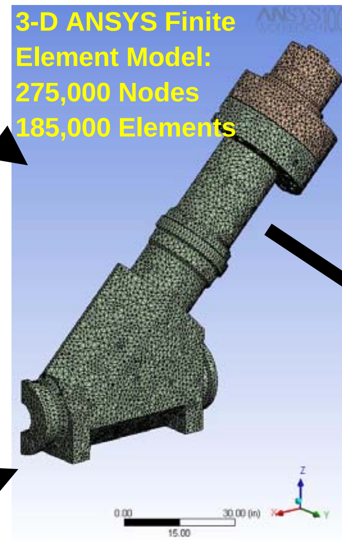
Picture of Frost Line After 23 Hours of Chilling

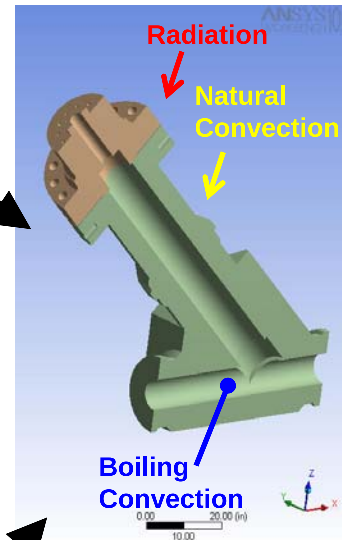


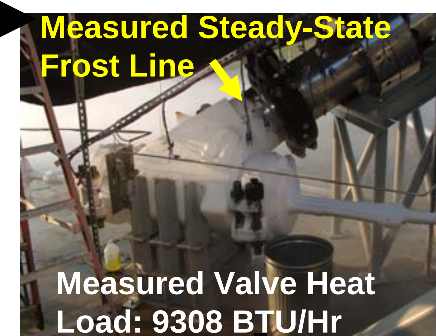
Thermal Image of Valve After Test

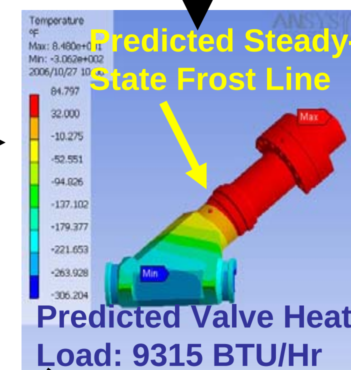
14” Valve
ANSYS Workbench Thermal Simulation

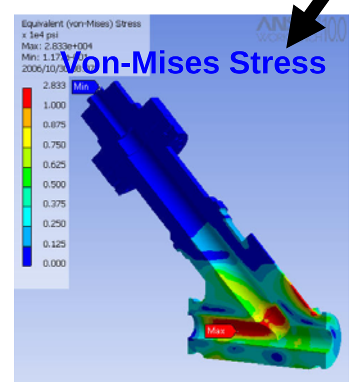
Geometry Description → Analysis Model → Loads & Boundary Conditions → ***Validated Results***

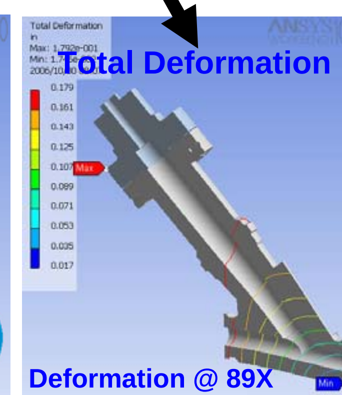




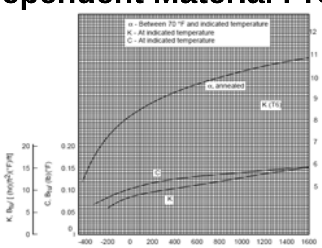




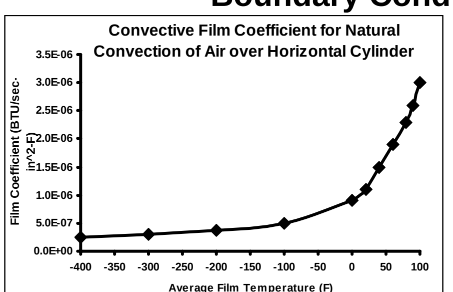


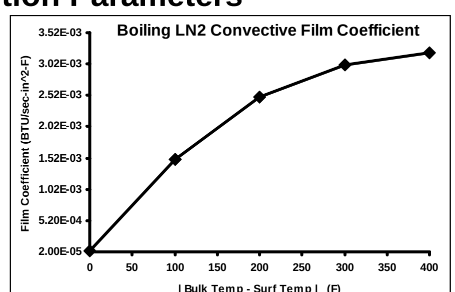


NIST / MIL-HDBK Temperature Dependent Material Properties



Empirically Based Temperature Dependent Boundary Condition Parameters



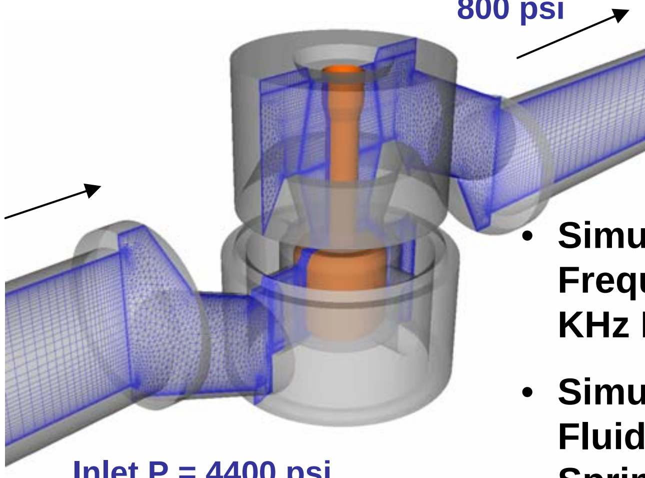


Computational Fluid Dynamics (CFD) Analysis

<u>Employ CFD Methodologies to Elucidate Select Propulsion Test Situations</u>

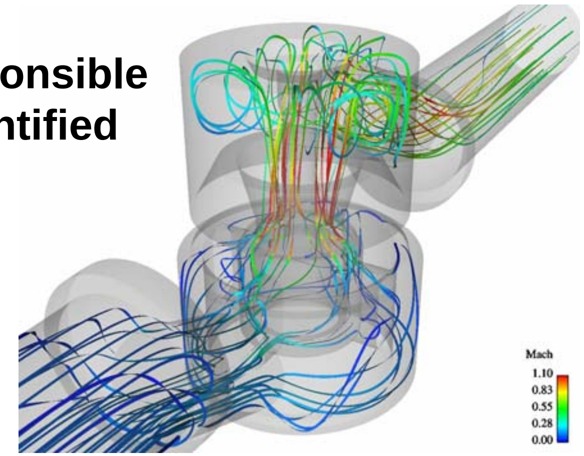
- Analyses of Valve Performance
  - Valves Can Vary from High Pressure Gaseous Valves to Valves Operating with Cryogenic Liquids
- Analyses of Valve Chatter
  - Unsteady Simulations of Pressure Regulator Valve
- Analyses of Valve Scheduling
  - Framework Developed for Moving Valve Calculations
  - Prediction of Valve Response to Plug operation
  - Valve Motion Specified as Plug velocity or Plug Displacement Curve
- Propellant Tank Mixing Behavior
  - Model Mixing Between Pressurization Gas and Liquid in a Run Tank
- Plume Dynamics
  - Model Interaction of Plumes with Facility Systems

Valve Chatter in Pressure Regulator Valve

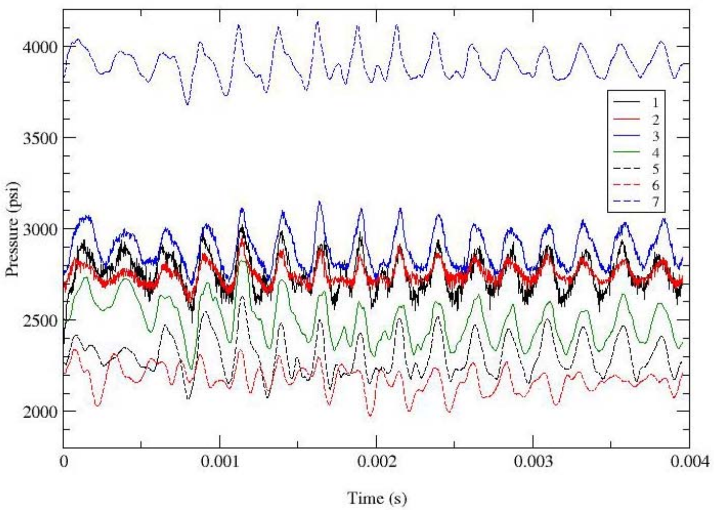


Axial Instability Responsible for Chatter Was Identified

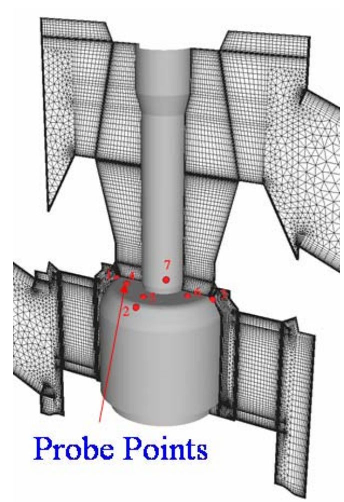
- Simulation Identified a 4 KHz Frequency; During Testing a 6 KHz Frequency Was Observed
- Simulation Did Not Account for Fluid-Structure Interaction or Spring Loading of Poppet

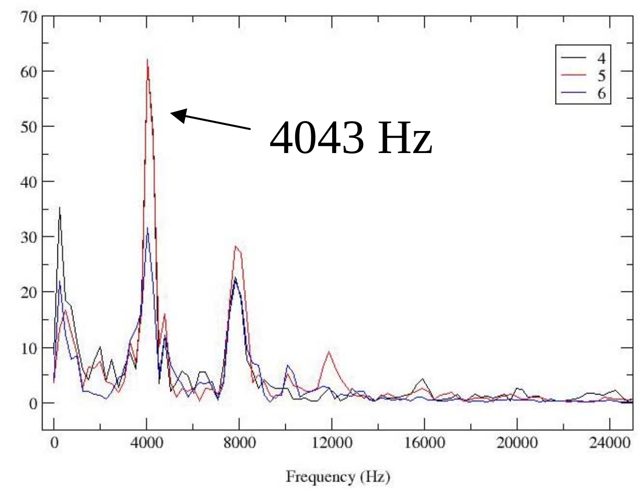


Stream Traces



Pressure Traces on Various Probe Points on the Poppet Indicating a Global instability





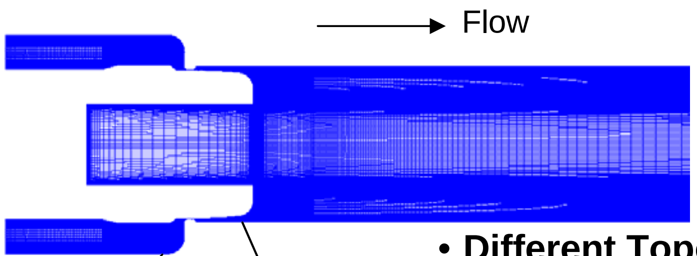
FFT of Pressure Traces Indicating a 4 KHz Chatter Frequency

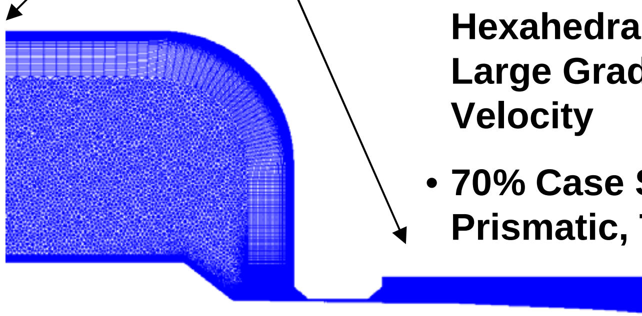
Overview of Framework for Valve Scheduling

- Automated Grid Motion with CRUNCH for Multi-Element Unstructured Grids
- A Library of Discrete Grids is Maintained That Define the Path of the Motion
  - This Permits Grid Topology to Change and Adapt to Requirements of Flow Physics Along Path of Motion
  - For Example, a Valve Which is 5% Open Has Different Mesh Requirements and Topology from a Valve That is 80% Open
  - Distortion of Grids is Minimized During Grid Motion
  - The Number of Grids Required in the Library is Kept to a Minimum
- Grid Motion Between the Library Grids is Carried Out with a Generalized Mesh Motion Solver Utilizing the Equations of Elasticity
  - Grid Motion is Carried Out Between Successive Library Grids
  - Solution is Interpolated onto New Library Grid When One is Encountered
  - Entire Procedure Works in Parallel Processor Environment and is Transparent to the User
- Procedure Maintains Solution Accuracy and is Very Robust

Variable Topology Issues With Grid Motion

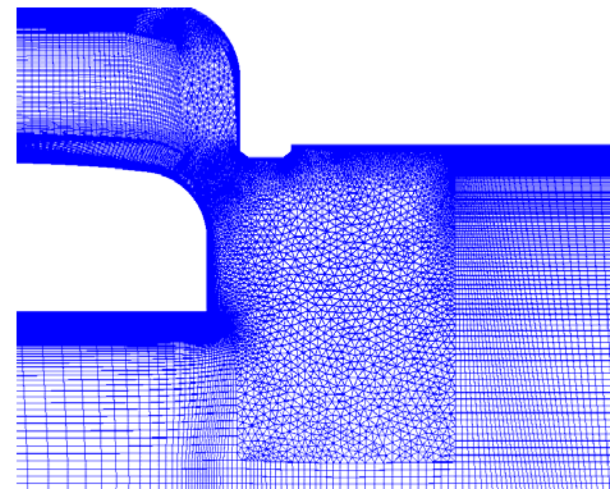
Cryogenic Valve at 8% Open



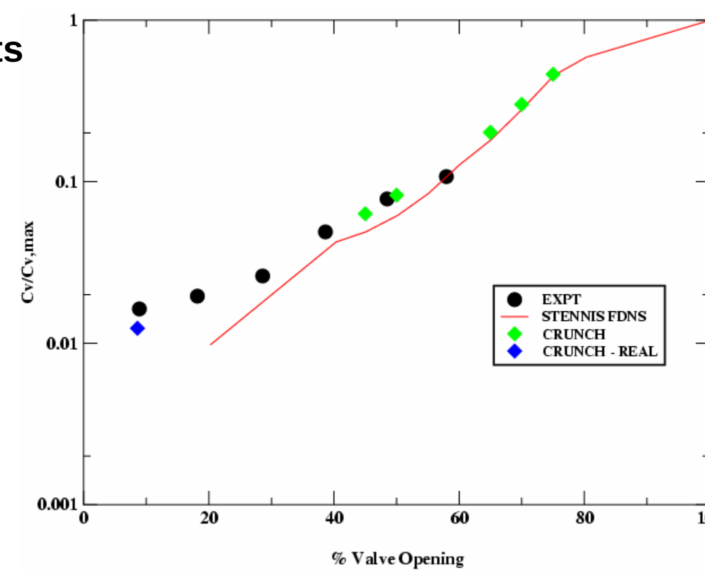


- Different Topologies at Different Plug Settings
- 8% Case Seat Region Has All Hexahedral Cells to Resolve Large Gradients in Pressure & Velocity
- 70% Case Seat Region Has Prismatic, Tetrahedral Elements

Cryogenic Valve at 70% Open



- LOX Valve – Cv is Compared with Experimental Data and FDNS Code at Different Discrete Settings
- CRUNCH CFD is in Excellent Agreement with Data – Plot is in log scale for Cv
- At Small Openings Density is Strongly Influenced by Pressure. These Real Fluid Effects Captured in CRUNCH Simulation – FDNS Diverges at Openings Smaller than 20%

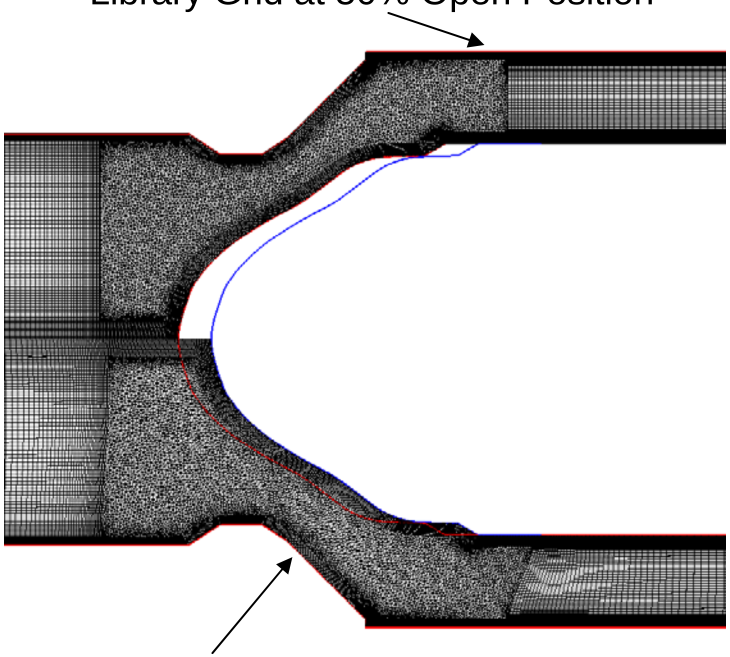


New Procedure for Moving Valve Simulation

For Generalized CFD Analyses of Moving Valve Problems, Such as Valve Scheduling, Valve Stall & Valve Instabilities, a Library Grid Approach is Taken in Conjunction with Grid Movement. This Permits Use of Variable Grid Topology & Permits Accurate Representation of Valve Flow Fields in the Seat Region Especially at Small Valve Openings Where Seat Dynamics Dominate. The Procedure is Illustrated Below:

Step 1

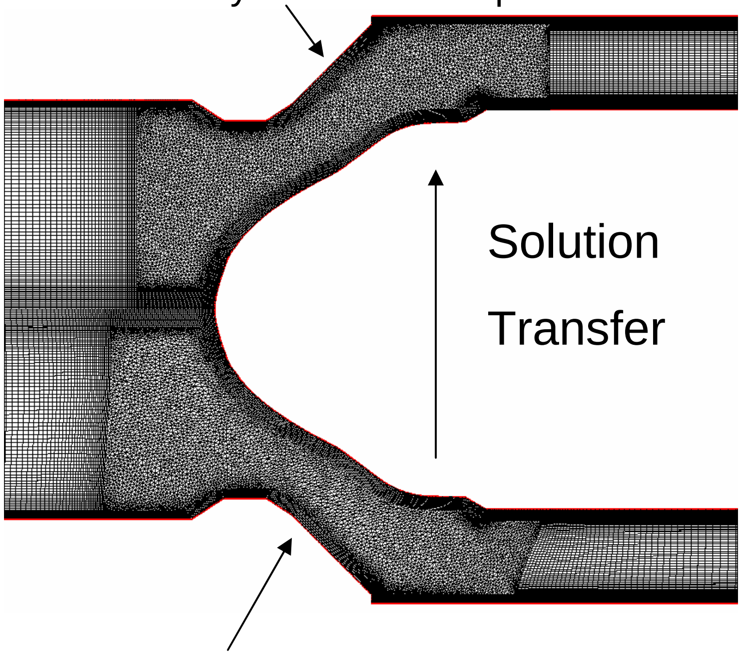
Library Grid at 50% Open Position



Automated Mesh Motion Using Stress Based Solver Moves Grid from 50% Open to 60% Open

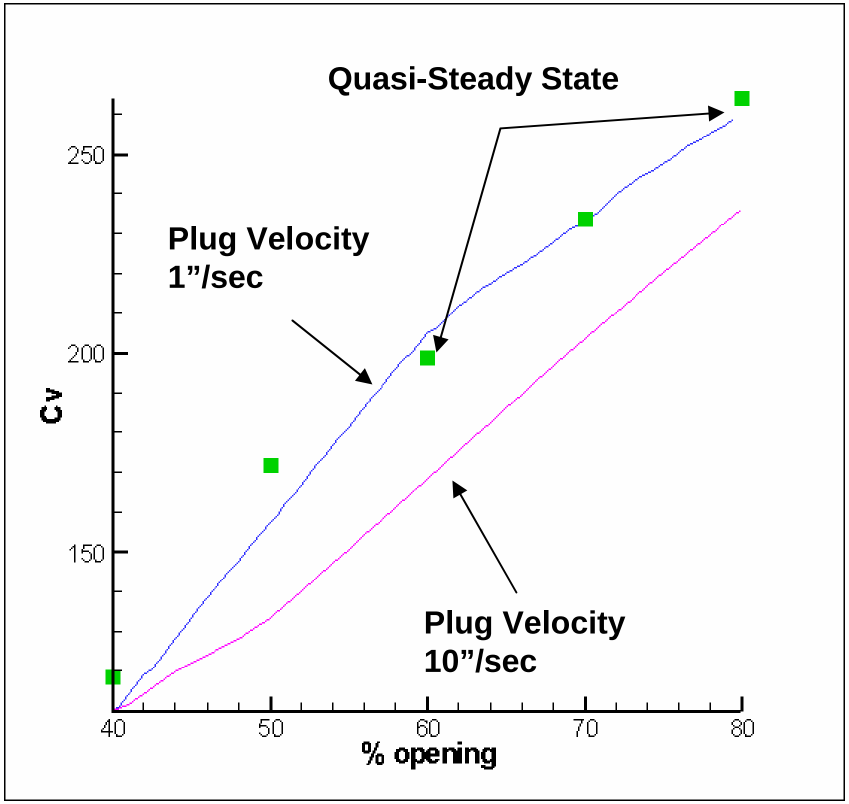
Step 2

Library Grid at 60% Open Position



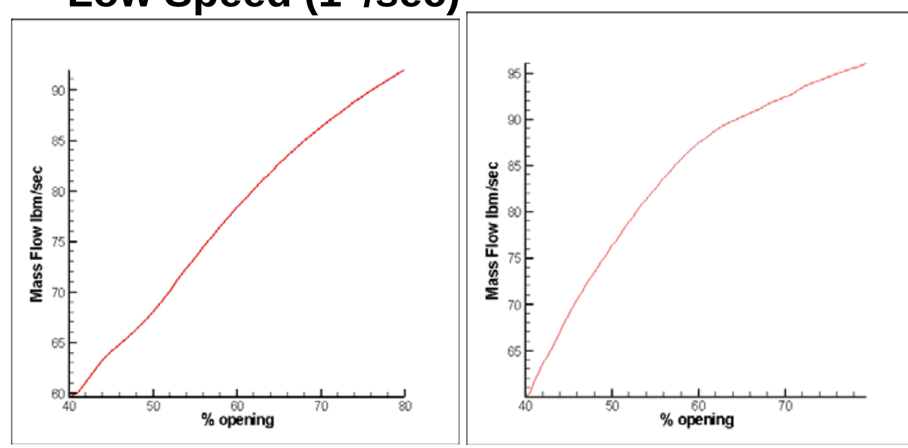
Distorted Mesh at 60% Open Position

SPLIT BODY VALVE SCHEDULING



Simulation with Slow Plug Velocity Matches Quasi-Steady State Solution – At Faster Rates Flow Responds More Slowly to Valve Motion

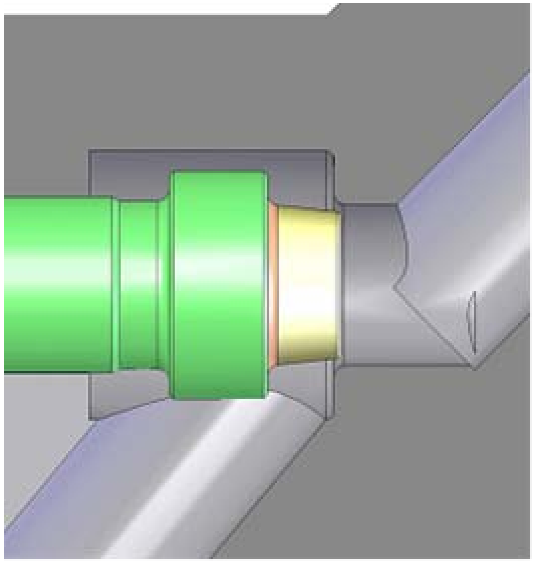
- One of Important Aspects of Moving Valve Simulations is the Reduction of Activation Tests Required to Predict Valve Response. This is Shown by the Different Cv and Mass Flow Rate Curves at Different Valve Operating Speeds.
- As a Validation We Also Use the Steady State Valve Cv Points to Compare Against the Cv for a Valve Operating at Low Speed (1”/sec)



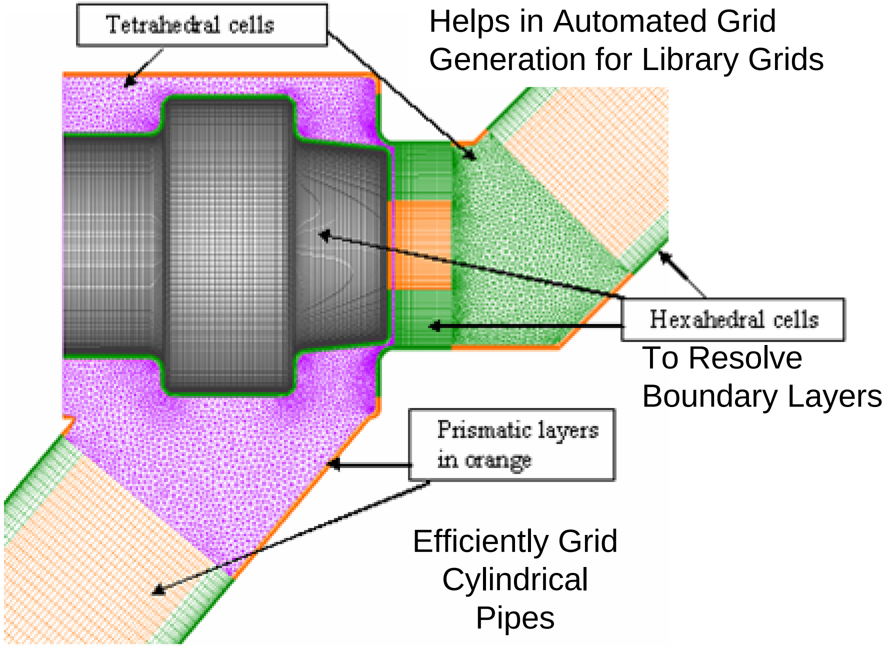
Mass Flow Variation with Opening at Different Operating Speeds

4-INCH Y-PATTERN VALVE ANALYSES

Configuration

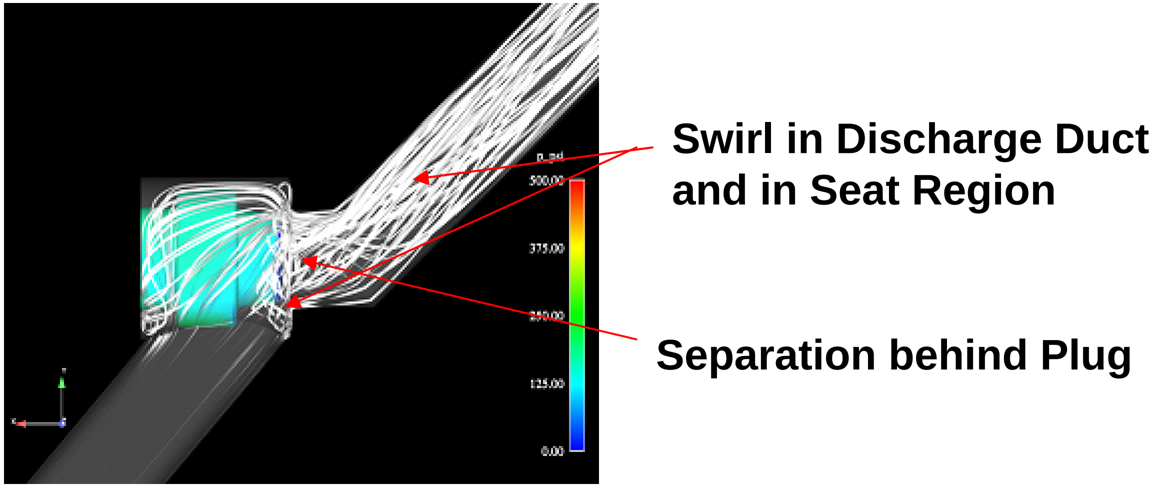


Multi-Element Grid

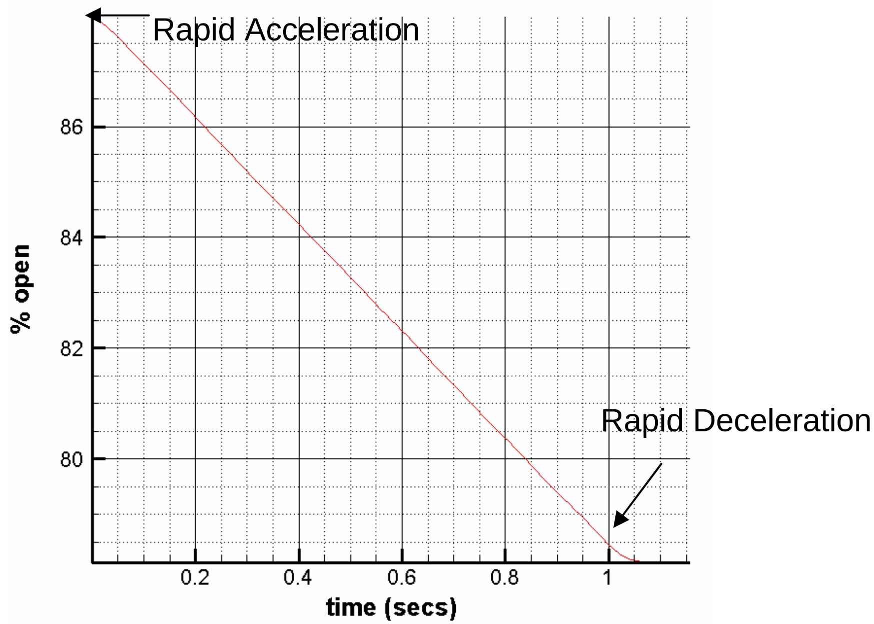


Results

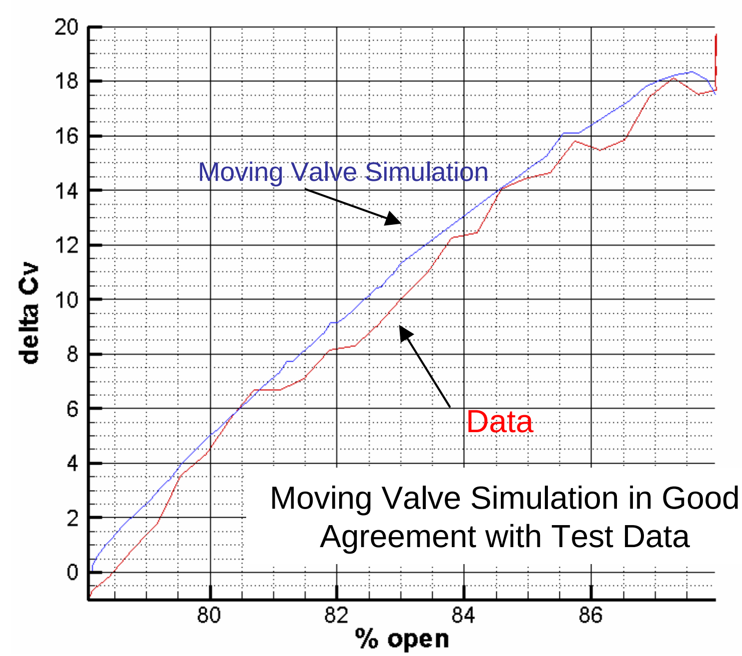
- **Flow Solution for Valve Operating in “Flow Over Plug” Mode**



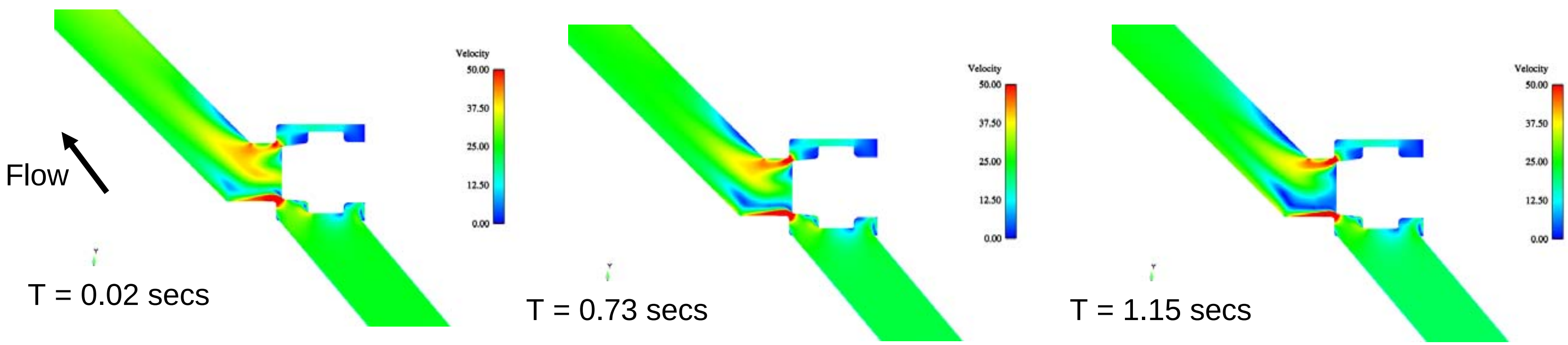
4-INCH Y-PATTERN VALVE SCHEDULING



Displacement Curve for Plug Motion



Variation of Cv with Valve Motion



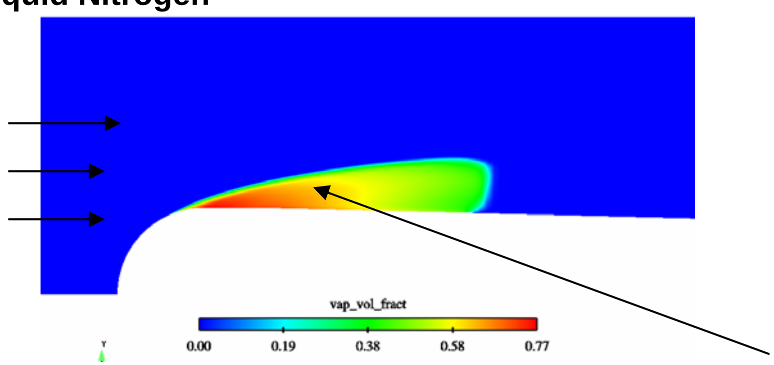
Velocity Distribution (m/s) in Moving Valve. As Valve Closes a Large Recirculation Develops Behind Plug Affecting Pressure & Consequently Cv.

Generalized Multi-Phase Computational Framework

- Computational Framework has Embedded Generalized Equation of State (EOS)
  - Properties Related to Sub-Critical & Supercritical States Are Obtained Directly from HBMS EOS or Sandia (Joe Oefelein) Based on Cubic EOS
  - Phase Change Problems such as Cryogenic Cavitation Modeled
  - Tank Pressurization Problems that Require Supercritical States for the Pressurant & Sub-Critical Gas/Liquid Properties for the Ullage Propellant Can Also Be Handled

<u>Cryogenic Cavitation</u>

Liquid Nitrogen

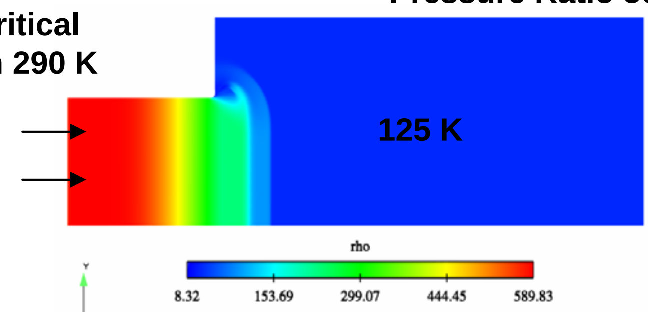


Formation of Vapor Cavity; Temperature Depresses as a Consequence of Cryogenic Cavitation

<u>Supercritical Flow in Chamber with Sub-Critical Conditions</u>

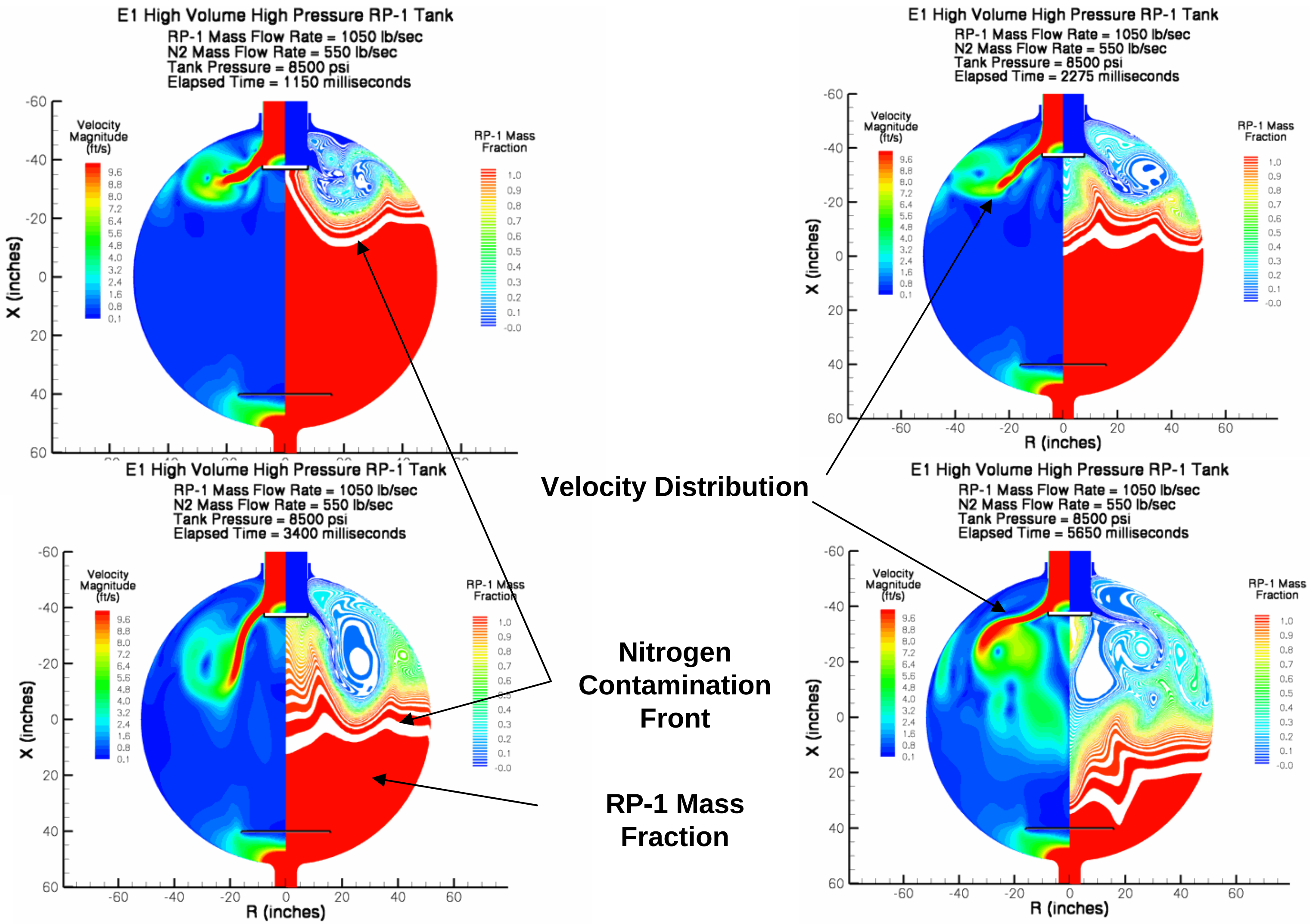
Pressure Ratio 50:1

Supercritical Oxygen 290 K



Propellant Tank Modeling

Evolution of RP-1 Pressurization with Nitrogen



Summary

- SSC has Developed a Suite of Effective Analytic Modeling and Analysis Tools Providing High Fidelity Assessment of Test Stand Performance
  - Rocket Propulsion Test Analysis (RPTA) Model, a 1-D Propellant System Analyzer
  - CFD Successfully Applied to Select Propulsion Test Situations Including Valves, Feed Line and Propellant Tank Scenarios
  - Finite Element Analysis (ANSYS)
- Analytic Tools Exercised Regularly on a Variety of Propulsion Test Projects by Experienced Analysts
  - Active Test Facilities (1.0 to 1.5 Mlbf Thrust, 8500 psi LOX/LH/RP-1 Supply)
  - Active Test Projects (e.g., J-2X PPA, J-2X at PBS, TGV)

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